LCA Methodology

Aid for Aggregating the Impacts in Life Cycle Assessment

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Abstract

Background and Objectives. Multiple Criteria Decision Aid (MCDA) methods may be employed in a great number of fields. Life Cycle Assessment (LCA) is a specific method among the MCDA Methods. A stage of MCDA methods to be respected in LCA is the comparative evaluation of the environmental impacts. This stage is the most difficult to implement because it is a question of estimating the global environmental impact of the life cycles studied. To achieve this purpose, it is necessary to model the environmental impacts and to apply a Multicriteria Analysis (MCA) method. The problem is to choose the most suitable among the available MCA methods. The objective of this paper is to help the LCA practitioner to make this choice.

Methodology. The MCA methods are compared according to their non-compensatory degree, their sensitivity to thresholds, their practicability and their workability.

Results and Conclusion. The protocol presented in this paper allows to choose the most appropriate MCA method for a given LCA according to the four previous criteria. This choice will depend on the priorities of the decision maker with concern to the comparison criteria.

Keywords: Aggregation; impact valuation; multicriteria analysis (MCA) method; multiple criteria decision aid (MCDA)

1 Background and Objectives

The results of LCA are often difficult to interpret and very controversial, especially at the phase of impact evaluation. It is a downside that may be reduced by applying a Multicriteria Analysis (MCA) method [1].

MCA methods use some weighting factors and their choice involves ideological and ethical values, which cannot be determined objectively. This difficulty is one of the sources of LCA limitations [2]. In order to avoid a choice of weighting factors at random, and to increase acceptance amongst the decision makers, several different methods were proposed [2,3]. From a broader perspective, LCA may also be described as a Multiple Criteria Decision Aid (MCDA) method [4]. The 'subjective' parts of LCA, i.e. the objective and scope definition as well as valuation, are the most obvious parts of LCA to benefit from a decision-analytical approach [5]. Pictet proposed a multicriteria decision-making tool that can be applied to environmental evaluation [6]. It is compared to the structure of LCA [7] in **Table 1**.

Table 1: Analogy between LCA and MCDA method

LCA [7]	Multiple Criteria Decision Aid [6]
1. Goal and scope definition	1. Definition of the objectives 2. Definition of the systems to be compared
2. Inventory analysis	4. Criteria evaluation
3. Impact analysis	
3.1. Impact classification	3. Building of a coherent family of criteria
3.2. Impact characterization	4. Criteria evaluation
3.3. Impact valuation/aggregation	5. Modeling the preferences and aggregating the results of the criteria
4. Interpretation	6. Sensitivity and robustness analyses
LCA does not perform this part of decision making Application of the decision	7. Synthesis of results and formulation of recommendations

A detailed scheme of an MCDA method involves the following stages:

1. **Definition of objectives:** Roy proposed three main problems of multiple criteria [8]. Following his definition, problem α corresponds to a procedure of selection, problem β corresponds to a procedure of sorting and problem γ is a procedure of ranking.

2. **Definition of the systems to be compared**

3. **Construction of coherent family of criteria:** the family has to fulfill the requirements of exhaustiveness, cohesion and non-redundancy [8].

4. **Criteria evaluation:** before the criteria evaluation itself, this stage requires an inventory analysis.

5. **Multicriteria analysis (MCA); modeling the preferences and aggregating the results of the criteria evaluation:** if the comparison is not made criterion by criterion, which has the advantage of keeping transparency, but makes evaluation difficult [9], some criteria may be aggregated between them. In that case, the interpretation may be easier but with less transparency. If aggregation is required, there is still the issue of choosing which MCA method to apply given the existence of a lot of methods.

6. **Sensitivity and robustness analysis:** these two types of analysis differ in their objectives. The sensitivity analysis studies the influence of the variations of the initial input data or the parameters which characterize the discriminating power of each criterion [10]. The method will be considered sensitive if a variation of the initial values involves a modification of the results. The robustness analysis studies the influence of the variations of some parameters that characterize the relative importance of the various criteria. The results of an MCA method are robust if variations in these parameters do not involve variations and the results can be obtained by everybody. If not, it is necessary to specify which set of parameters the results are dependent on. The potential variations of the results are not dependent on the method, but only on the evaluations obtained for every criterion.

7. **Synthesis of results and formulation of recommendations:** this is an interpretation step that allows the preparation of some recommendations.

It appears that LCA is a particular MCDA and that we can then apply an MCA (stage 5 of the MCDA) to LCA. The purpose of this paper is to guide the practitioners to choose the appropriate MCA method for LCA applications. This work focuses on the different MCA methods used to aggregate the criteria evaluations (stage 5). The methodology that allows the comparison of MCA methods between one another is subsequently presented. The final section of the paper is devoted to the development of the resulting protocol of the choice of an MCA method for LCA.

2 Aggregating the Criteria Evaluations

2.1 Criteria

To compare two systems *a* and *b*, the decision maker preferences may be represented by the following four elementary binary relations (I, P, Q, R) [8]:

1. *a I b* (indifference situation): *a* is indifferent to *b*,
2. *a P b* (strong preference situation): *a* is strictly preferred to *b*,
3. *a Q b* (weak preference situation): it is the hesitation between the indifference and preference situations and not being sure that (*a P b*) [8],
4. *a R b* (incomparability situation): for instance, there is a lack of information about *a* and *b* to compare them or its evaluation for a given criterion is judged unacceptable to keep this system as a solution to the problem, no matter its evaluation for the other criteria.

These preferences are based on the comparison of the consequences of the systems. The criteria represent the consequences of the different systems that will allow one to judge them. A criterion is therefore a function *g* defined on the set *A* of systems. Let us note *g* as a criterion and *g*(*a*) as the evaluation of the system *a* for the criterion *g*. We want to compare two systems *a* and *b* on this criterion *g*. The scale is based on the environmental case: the smaller the criterion evaluation, the better the performance of this criterion.

Table 2: Classification of criteria [12]

Conditions on p and q	Kind of criteria
q=p=0	true criterion
q=p≠0	semi-criterion
q=0, p≠0	precriterion
q≠0, p≠0, q<p	pseudo-criterion
p: preference threshold, q: indifference threshold	

To take into account that the numerical values of systems of some criteria are subjected to imprecision, indetermination and uncertainty phenomena, Roy [8] has defined two thresholds q and p. q is the indifference threshold and p is the preference threshold. q is interpreted as the minimum margin of imprecision associated with a given criterion and p as the maximum margin of error associated with the criterion in question [11]. In LCA, q characterizes the uncertainty on the impacts and p is proportional to q according to **Table 2**.

The decision maker can establish that the different criteria do not have the same relative importance. In order to express this choice, he can refer to three processes: the weighting factor, w, hierarchical structure and the veto threshold v. Weighting is the process of converting criteria evaluation of some criteria by using numerical factors based on choices of values. Higher is the value of a weighting factor, more important the criterion is considered. The hierarchical structure consists in putting the criteria in relative importance order. The veto threshold allows the exclusion of a system if its evaluation for a given criterion is judged unacceptable to keep this system as a solution to the problem, no matter concerning its evaluation for the other criteria. Unlike the weighting factor, higher is the value of a veto threshold, less important is the criterion. The results will be robust if they are not depending on these parameters. The general representation of a criterion is given in **Fig. 1**.

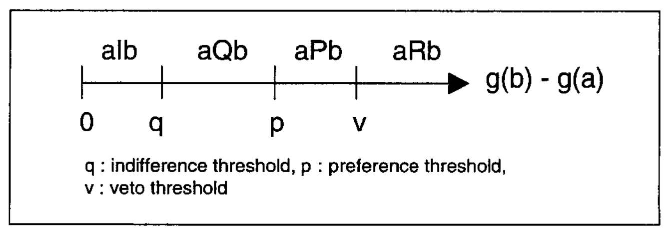

Fig. 1: Representation of a criterion

2.2 Aggregating the criteria evaluations through MCA method

The MCA methods can be assigned to one of the three following categories: (i) the single criterion approach and (ii) the outranking approach and (iii) the methods based on 'interactive judgments with trial-and-error iteration' [13]. This third category is not applicable to LCA because, while the first two groups embody a clear mathematical structure, the third one is not referred to any formalized or automatic procedure. Emitted judgments have only a local consequence, which is not valid in LCA.

2.2.1 The single criterion approach

The global preferences modeling is defined by an aggregation function U that represents at best the decision maker preferences: $g(a_i) = U [g_1(a_i); g_2(a_i); \ldots ; g_n(a_i)]$ where, in LCA, a_i are the product systems or scenarios 'i', g_j are the environmental criteria 'j', U is an aggregation function and g is the global index. Among the usual aggregation functions, we can mention the Multi Attribute Utility Theory [14] (MAUT) that allows the aggregation of values obtained by assessing partial functions on each criterion to establish a global utility function U (arithmetic mean, geometric mean,...). MAUT offers a well-developed mathematical structure for describing preference tradeoffs for different attributes taking into account risk attitudes and environmental criteria levels. It is more sophisticated and realistic than the assignment of simple weighting factors in LCA [4]. It has been applied to LCA in [5], [15] and [16].

2.2.2 The outranking approach

The methods based on this approach aim at the aggregation of the decision maker preferences established when comparing alternatives within each criterion. The outranking relation *aSb* (a outranks b) holds when there is a strong reason to believe that with respect to all the criteria, *a* is at least as good as *b*, with no reasons that absolutely prevent one from making such a statement [17]. Considering the use of thresholds (q, p and v) and the hypotheses about the properties of the relations (intransitivity, ...), the outranking approach leads to different order structures depending on the preference relations taken into consideration. Contrary to the first approach, this one allows the incomparability. The ELECTRE method was the first one to use an outranking approach and many others such as the different ELECTRE and the PROMETHEE methods which followed it. Other methods such as ORESTRE, REGIME and MELCHIOR, which are based on the same concepts as ELECTRE, are considered ordinal. **Table 3** summarizes some of these MCA methods based on the outranking approach.

3 Comparing Multicriteria Analysis Methods

3.1 Definition of comparison criteria

This comparison stage, on the one hand, allows one to eliminate the MCA methods that are somewhat usable in LCA and, on the other, to establish which methods to use for LCA. Four comparison criteria have been used to select pertinent methods among the different possible methods:

(a) **Non-compensation:** The aggregation of the evaluation of the alternatives expressed according to different dimensions implies some compensation. Furthermore, to choose an MCA method is to choose a kind of compensation. From an intuitive standpoint, the compensatory aspect of a method translates the relation that a good evaluation on one criterion makes up for a bad evaluation on another one. But there are no unanimous definitions or principles to characterize the degree of compensation. We can state that all MCA methods can be either compensatory or partially compensa-

Table 3: Comprehensive list of different known outranking methods

Method	References	Description
ELECTRE I	[13]	The concept of outranking relationship is used. The procedure seeks to reduce the size of non-dominated set of alternatives (kernel). The idea is that an alternative can be eliminated if it is dominated by other alternatives to a specific degree. The procedure is the first one to seek to aggregate the preferences instead of the performances.
ELECTRE IS	[13]	This procedure is exactly the same as ELECTRE I, but it introduces the indifference threshold.
ELECTRE II	[13]	ELECTRE II uses two outranking relations (strong and weak)
ELECTRE III	[13]	The outranking is expressed through a credibility index
ELECTRE IV	[13]	The procedure is like ELECTRE III, but used hierarchical structure
ELECTRE TRI	[13]	The procedure is like ELECTRE III, but did not use the conjunctive and disjunctive techniques to affect the alternatives to the different categories (ordered).
PROMETHEE I	[13]	PROMETHEE I is based on the same principles as ELECTRE and introduces six functions to describe the decision maker preferences along each criterion. This procedure provides a partial order of the alternatives using entering and leaving flows.
PROMETHEE II	[13]	PROMETHEE II is based on the same principles as PROMETHEE I. This procedure provides a total preorder of the alternatives using an aggregation of the entering and leaving flows.
EXPROM I	[18]	EXPROM I is an extension of the PROMETHEE I method. This extension consists of a more detailed investigation of the differences existing among the performances of the systems examined, achieved through the notion of ideal and anti-ideal alternatives.
EXPROM II	[18]	EXPROM II is an extension of the PROMETHEE II method. This extension consists of a more detailed investigation of the differences existing among the performances of the systems examined, achieved through the notion of ideal and anti-ideal alternatives.
MELCHIOR	[13]	MELCHIOR is an extension of ELECTRE IV
NAIADE	[19]	The impact or evaluation matrix may include either crisp, stochastic or fuzzy measurements of the performance of an alternative A with respect to a criterion g.
QUALIFLEX	[13]	This procedure uses successive mutations to provide a ranking of the alternative corroborating with the ordinal information.
Trichotomic segmentation	[20]	The terminology 'methodology' would be the most appropriate term. It allows one to approach the problematic β based on outranking.
ORESTE	[13]	This procedure needs only ordinal evaluations of the alternatives and the ranking of the criteria in term of importance
REGIME	[13]	A pairwise comparison matrix is built using +1 if there is dominance, 0 if the two alternatives are equivalent and −1 for the negative dominance. The aggregation of these weighed scores provides a total preorder of the alternatives.

tory [21]. In the case of compensatory MCA methods, one admits that an absolute compensation among the different evaluations may exist. All single criterion methods fall into this category. On the contrary, the outranking methods are much less compensatory than the single criterion methods because they promote medium actions to the detriment of actions that are very good on some criteria and very bad on others. From our viewpoint, in environmental assessment, the compensation has to be avoided as much as possible because a very serious impact on one ecosystem cannot be compensated by a insignificant on another [22]. So, the outranking methods are very interesting in the case of LCA application. The major problem is to evaluate the degree of compensation for each of these outranking methods.

(b) Sensitivity to indifference and preference thresholds: only the indifference and the preference thresholds are considered here. The LCA practitioner and the decision maker are searching for a method sensitive enough to thresholds.

(c) Practicability: this notion is estimated by the LCA practitioner and includes the level of knowledge and the time required to apply the method as well as the easiness with which a physical sense can be attributed to the constants that need to be fixed arbitrarily a priori.

(d) Workability: this notion is estimated by the decision maker and is bound to the results of readability, the easiness for interpretation and the transparency of the method. Readability depends on the visual quality of the presentation of the results.

3.2 Preliminary selection

We saw that the 'interactive local judgments with trial-and-error' methods were not applicable for LCA. They have already been eliminated from our study. Nonetheless, a number of methods remain including the single criterion approach and the outranking approach. We decided to limit our study to only one of these two approaches. According to the previous comparison points (non-compensation, sensitivity, practicability and workability), we showed that the outranking methods are very interesting in the case of LCA application because they are only partially compensatory. Consequently, we concentrated our study on these outranking methods and we excluded the single criterion methods.

Among the outranking methods, three of them (the QUALIFLEX, Trichotomic Segmentation and ORESTE methods) were eliminated because of their poor practicability. The REGIME method was also excluded. Therefore, only the ELECTRE, PROMETHEE, EXPROM, NAIADE and MELCHIOR methods have been studied on the basis of the four viewpoints previously presented. To be able to compare the NAIADE method with the other methods, one has to exclude the capability of the method to model uncertainties. Only crisp evaluation scores will be considered. The results are presented with this hypothesis.

3.3 Comparison by non-compensation

To compare the different MCA methods according to non-compensation, we built a fictitious application with five systems graded a_i and eight environmental criteria graded g_j. As in every environmental application, the sense of preferences is decreasing: the lower the evaluations, the better the environmental performance. In order to show the non-compensation to advantage, the system's profiles are characteristic:

- a_1 and a_2 are completely antagonistic. a_1 corresponds to the best profile for j=1 to j=4 and the worst for j=5 to j=8. a_2 represents the opposite profile,
- a_3 is the medium system,
- a_4 evaluation decreases regularly on each criterion with $g_1(a_4)=1.15 * g_1(a_3)$ and $g_8(a_4)=0.85 * g_8(a_3)$,
- a_5 evaluation is equal to $1.1 * g_j(a_3)$ for j=1 to j=4 and to $0.9 * g(a_3)$ for j=5 to j=8.

Through these profiles, we want to test the power of the MCA method to distinguish the global performances of symmetrical systems and then, indirectly, their compensatory aspect.

The q_j thresholds were chosen in order to always have a significant gap between the evaluations (except for a_3 and a_4 equal on criteria g_4 and g_5): $\forall j$, $q_j = 0.04 * g_j(a_3)$. The p_j thresholds are proportional to q_j: $\forall j$, $p_j = 2.25 * q_j$. The veto thresholds were chosen so that a_1 and a_2 have assessment differences, with respect to the other ones, higher than the other veto thresholds for at least one criterion and that a_3, a_4 and a_5 have assessment differences among them lower than the other veto thresholds for each criterion. In this way, $\forall j$, $v_j = 0.30 * g_j(a_3)$. The weighting factors were fixed to 1 for each criterion. Moreover, the ELECTRE TRI and NAIADE methods lie on reference systems. The reference systems for the two methods are the same and equal to +/-25% for the median system a_3. So, $\forall j$, $g_j(ref_1) = 1.25 * g_j(a_3)$ and $g_j(ref_2) = 0.75 * g_j(a_3)$. The corresponding matrix is reported in **Table 4**. Values are purposely very precise in order to respect the absolute symmetry of systems. **Fig. 2** repre-

Table 4: Comparison by non-compensation: evaluation matrix with indifference, preference and veto thresholds and reference systems

	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8
a_1	225.000	20.0	90.000	2.40	0.2500	0.1000	90.0	300.00
a_2	90.000	10.0	45.000	0.60	1.0000	0.2000	180.0	750.00
a_3	157.500	15.0	67.500	1.50	0.6250	0.15000	135.0	525.00
a_4	181.125	16.5	70.875	1.50	0.6250	0.1425	121.5	446.25
a_5	141.750	13.5	60.750	1.35	0.6875	0.1650	148.5	577.50
q_j	6.300	0.60	2.700	0.060	0.02500	0.0060	5.40	21.00
p_j	14.175	1.35	6.075	0.135	0.05625	0.0135	12.15	47.25
v_j	47.250	4.50	20.250	0.450	0.18750	0.0450	40.50	157.50
ref_1	196.875	18.75	84.375	1.875	0.78125	0.1875	168.75	656.25
ref_2	118.125	11.25	50.625	1.125	0.46875	0.1125	101.25	393.75

a_i: systems, g_j: environmental criteria, q_j: indifference thresholds ($\forall j$, $q_j = 0.04 * g_j(a_3)$), p_j: preference thresholds ($\forall j$, $p_j = 2.25 * q_j$), v_j: veto thresholds ($\forall j$, $v_j = 0.30 * g_j(a_3)$), ref_1 and ref_2: reference systems ($\forall j$, $g_j(ref_1) = 1.25 * g_j(a_3)$ and $g_j(ref_2) = 0.75 * g_j(a_3)$)

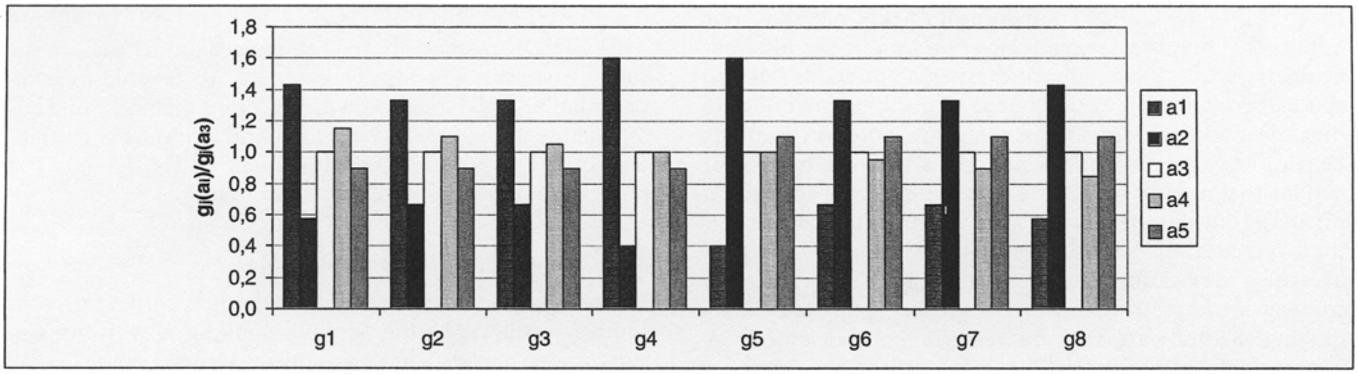

Fig. 2: Comparison by non-compensation: normalization of the criteria in comparison with the median system a_3

sents the normalization in comparison with the median system a_3 for each criterion and each system.

Fig. 2 allows to see that it is impossible to determine which system(s) is(are) the best one(s) if the comparison of systems is made criterion by criterion. Moreover, $\forall i$,

$$\frac{\sum_{j=1}^{j=8} \frac{g_j(a_i)}{g_j(a_3)}}{8} = 1 .$$

The arithmetic means with all weight equal to 1 shows that all the systems are equivalent, implying a strong compensatory degree which has to be avoided.

Conversely and according to the matrix construction, a non-compensatory method would have produced the statements in **Table 5**. We attributed some scores (1 or 2) to the previous statements. The higher the score, the higher the importance of the statement. The global score of a non-compensatory method is then 7.

In order to appreciate the non-compensatory effect of the different outranking methods, each outranking method has been applied with this fictitious application. For each result, some affirmations of Table 5 are respected. It allows one to grade each outranking method according to the respected affirmations. The higher the global score for the tested outranking method, the less compensatory the method. Results are presented in **Table 6**.

Table 5: Comparison by non-compensation: results corresponding to a non-compensatory method

Results of not compensatory method	Score if affirmation is respected
(1) a_1 and a_2 are incomparable between them (the veto thresholds are overtaken),	2
(2) a_1 and a_2 must be worse than the others. It is more interesting to privilege a system medium on all criteria than a system excellent on some criteria and very bad on the other ones,	2
(3) a_1 and a_2 must be incomparable with the other ones,	1
(4) a_4 and a_5 must be incomparable or equivalent,	1
(5) a_3 and a_4 must be judged better than the other ones.	1
Global score of a non-compensatory method	7

Table 6: Comparison by non-compensation: results of the application of the outranking methods and estimation of the non-compensation of each outranking method

Outranking method	Results	Global score of non-compensation	Outranking method	Results	Global score of non-compensation
ELECTRE I	a_3Ia_4 and a_3Ia_5 all the other relations: a_iRa_j	4	PROMETHEE I	a_1Ia_2, a_1Ia3_5, a_2Ia_3 and a_3Ia_4 all the other relations: a_iRa_j	1
ELECTRE IS	a_3Ia_4, a_3Ia_5 and a_4Ia_5 all the other relations: a_iRa_j	4	PROMETHEE II	All the systems are equivalent	1
ELECTRE II	Direct ranking: (a_3 and a_4)Sa_5, a_5S(a_1 and a_2) Indirect ranking: a_5S(a_3 and a_4), (a_1 and a_2)Sa_5	2	EXPROM I	All systems are incomparable	4
ELECTRE III	All systems are equivalent	1	EXPROM II	All the systems are equivalent	1
ELECTRE IV	All systems are equivalent	1	MELCHIOR	a_3Ia_4, a_3Ia_5 and a_4Ia_5 all the other relations: a_iRa_j	4
ELECTRE TRI	Result 1: (a_3, a_4 and a_5)S(a_1 and a_2) Result 2: (a_1 and a_2)S(a_3, a_4 and 5	2	NAIADE	Result 1: (a_3, a_4 and a_5)S(a_1 and a_2) Result 2: (a_1 and a_2)S(a_3, a_4 and a_5)	2

a_i: systems, I: indifference, R: incomparability, S: outranking, global non-compensation score: higher this value, less compensatory the outranking method

Two of the ELECTRE methods (I and IS) are not very compensatory. For ELECTRE II, III, IV and TRI, no outranking is established, so the result implies a more compensatory effect than for the other methods. The MELCHIOR method also gave good results. This is due to the use of the veto thresholds that allow the elimination of the extremely poor systems in some criteria. The simplified NAIADE method applied here is fairly compensatory. The use of a compensation threshold that eliminates the extremely poor systems in some criteria is beneficial. In contrast, the antagonistic systems a_1 and a_2 are equivalent, which increases the compensatory degree. Three of the PROMETHEE and EXPROM methods are very compensatory because of the equivalence of a_1 and a_2. Moreover, these methods are very sensitive to the variations of the initial assessments. They are disadvantaged by the symmetric systems and would give better results in case of a real application, which has very few chances to be symmetric.

3.4 Comparison by sensitivity to indifference and preference thresholds

To compare the different MCA methods by their sensitivity to thresholds, we built a new fictitious application with three systems and three criteria. a_1 corresponds to an extreme system: it is best on g_2 and g_3 criteria and is higher than the veto threshold on g_1. In the same way, a_3 is best on g_1 and worst on g_2 and g_3. Finally, a_2 is an intermediate system.

Initial indifference, preference and veto thresholds have been fixed. The application of each outranking method with these initial thresholds gives a first result. Then we have varied the indifference and preference thresholds. The variations of the thresholds must respect the relation $q_j < p_j$. A variation of one threshold implies the invariability of the other ones. The criteria values and the threshold variation ranges are reported in **Table 7**.

Table 7: Comparison by sensitivity to indifference and preference thresholds: evaluation matrix with initial thresholds and variation range

	g_1	g_2	g_3
a_1	1500	0.2	50
a_2	1000	0.8	80
a_3	500	0.9	70
initial q_j	200	0.30	5
initial p_j	700	0.65	20
initial v_j	900	0.9	70
Δq	0–700	0–0.65	0–20
Δp_j	200–900	0.3–0.9	5–70

a_i: systems, g_j: environmental criteria, p_j: preference thresholds, q_j: indifference thresholds, v_j: veto thresholds

For each outranking method, the variation of a given threshold in comparison with the initial value can lead to a result different from the first one. In the variation range of each threshold, we determine the number of different results obtained. This number of different results corresponds to scores allocated to each variation threshold. The global score corresponds to the sum of scores obtained for each threshold variation. The higher the value, the more sensitive the outranking method. The results are reported in **Table 8.**

Table 8: Comparison by sensitivity to indifference and preference thresholds: number of different results by application of outranking methods versus each variation range of indifference and preference thresholds

Outranking methods	Δq_1	Δq_2	Δq_3	Δp_1	Δp_2	Δp_3	Global score
ELECTRE I	No thresholds						
ELECTRE IS	1	2	1	1	1	1	7
ELECTRE II	No thresholds						
ELECTRE III	2	1	1	2	2	2	10
ELECTRE IV	2	2	2	2	1	3	12
ELECTRE TRI	2	5	1	2	2	2	14
PROMETHEE I	1	2	1	2	2	1	9
PROMETHEE II	1	2	1	1	1	1	7
EXPROM I	1	2	1	1	2	3	10
EXPROM II	1	1	1	1	2	3	9
MELCHIOR	1	1	2	1	1	1	7
NAIADE	No thresholds						

Higher the value of global score, more sensitive the outranking method

Among all the ELECTRE methods, the most sophisticated ones are the most sensitive to thresholds. However, no distinction can be made between the two threshold variations, despite the fact that p_j is included twice and q_j only once in calculation. Between the PROMETHEE and EXPROM methods, the EXPROM ones are the most sensitive to thresholds because these parameters operate twice in calculation while they operate only once in calculations using the PROMETHEE methods. Moreover, versions I of these two methods are more sensitive than versions II because of the incomparability in versions I that does not exist in the versions II. Finally, in the MELCHIOR method, the thresholds are used only to determine the indifference, the weak and the strong preferences. As the results are presented only for one kind of preference, the p_j variation has therefore no influence and, globally, this method is the least sensitive to thresholds.

3.5 Comparison by practicability

The practicability is measured with respect to three criteria: (i) comprehension easiness, (ii) execution promptness, and (iii) physical reality of constants. Each criterion is graded from 1 to 3: where 1 corresponds to the worst grade and 3 to the best one. 9 is therefore the maximum and best score with regard to practicability. The results are reported in Table 9. Some methods such as ELECTRE III and IV may be applied by means of software. Here, all methods have been tested by a manual calculation that disadvantages the ELECTRE methods because of the long and fastidious calculations. The ELECTRE I and IS, NAIADE, MELCHIOR, PROMETHEE and EXPROM methods are more easily applicable because of few arbitrary constants to fix. The thresholds for the six kinds of criteria, for example, need to be fixed while the PROMETHEE and EXPROM methods can deal with them.

Table 9: Comparison by practicability and workability: estimation by means of comprehension easiness, execution rapidity and physical reality of constants for practicability and by means of results readability, interpretation easiness and transparency for workability

Outranking methods	Comprehension easiness	Execution rapidity	Physical reality of constants	Practicability	Results readability	Interpretation easiness	Transparency	Workability
ELECTRE I	3	3	2	8	2	1	3	6
ELECTRE IS	3	3	2	8	2	1	3	6
ELECTRE II	2	2	2	6	3	2	2	7
ELECTRE III	1	1	1	3	3	2	1	6
ELECTRE IV	1	1	1	3	3	2	1	6
ELECTRE TRI	2	2	2	6	3	3	2	8
PROMETHEE I	3	3	3	9	2	1	3	6
PROMETHEE II	3	3	3	9	2	3	3	8
EXPROM I	3	3	3	9	2	1	3	6
EXPROM II	3	3	3	9	2	3	3	8
MELCHIOR	3	3	3	9	2	1	3	6
NAIADE	2	2	3	7	3	3	2	8

For each outranking method, the higher the value of each column, the better the corresponding parameter and then practicability and workability

3.6 Comparison by workability

The workability is measured with respect to three criteria: (i) readability of results, (ii) easiness of interpretation, and (iii) transparency. The same grading system has been used as for the practicability. The higher the score, the better the workability. The results are reported in **Table 9**. Traditionally, the results are presented by a partial preorder that is difficult to interpret and does not give any information about the systems orders. For the ELECTRE II, III and IV methods, we used a new and more readable representation [23]. The ranking or sorting methods are the easiest to interpret. Those selected may be a source of confusion because they give a subset that includes the best system but also the systems incomparable to the rest of the methods. Concerning the transparency, the ELECTRE III method may appear somewhat unclear for the non-initiated LCA practitioner.

4 Protocol for Choosing the Most Suitable Multicriteria Analysis for LCA

The choice of the MCA method depends on the characteristics of LCA in which it takes place. Therefore, there are some questions that need to be solved with regard to the objective to be achieved and the assessment of the available matrix:

1. What is the objective of the study?
2. What is the type of criteria?
3. What is the type of data? Cardinal or ordinal? A priori, only the ELECTRE I method may use ordinal values. With some modifications, numerous other methods could accept such values.
4. Does the method use weighting or hierarchical structure? Must we attach more importance to some criteria than to another compared with the uncertainties that exist to the impact indicators validity level?

The response to these four questions allows the classification of the methods under different categories that are reported in **Fig. 3**. Guitouni and Martel [13] presented a guideline to help choosing an appropriate MCA method, but their study is not specific to environmental assessment and gives no indication as to go further in the choice concerning the four previous questions. For a given life cycle, the LCA practitioner can therefore determine a set of suitable MCA methods. A decision has to be made on the selected methods based

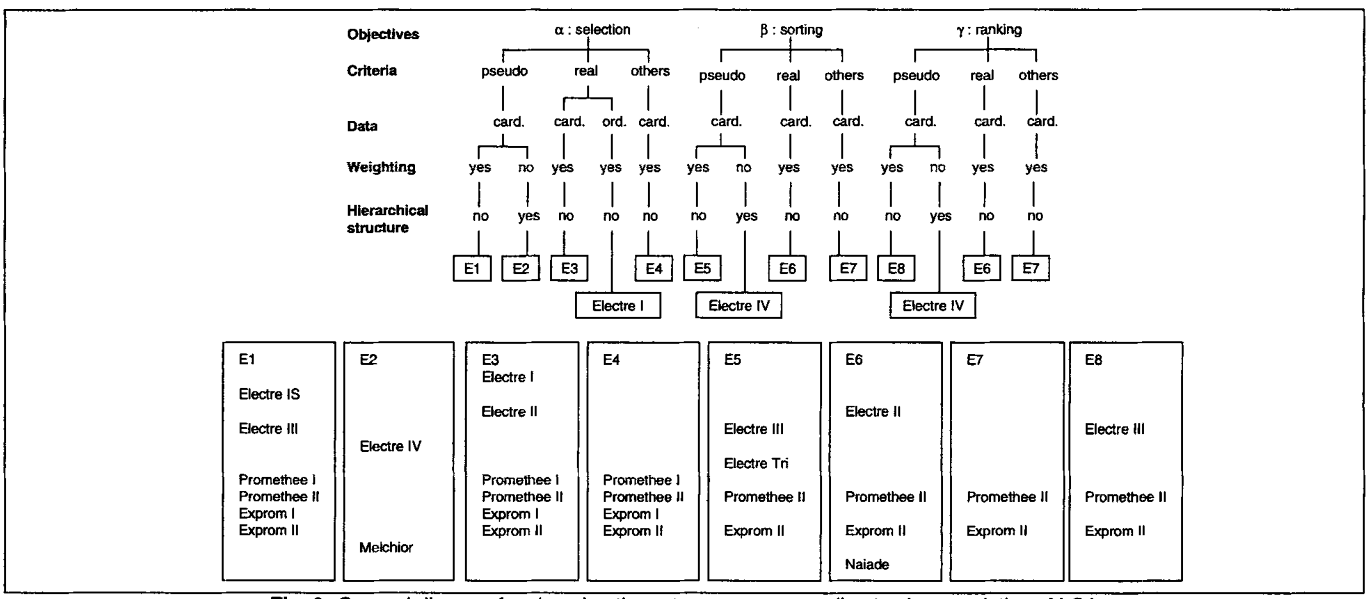

Fig. 3: General diagram for choosing the category corresponding to characteristics of LCA

Table 10: Ranking of methods regarding non-compensation, thresholds, practicability and workability

MCA method	Categories of the protocol	Non-compensation	Sensitivity thresholds	Practicability	Workability
ELECTRE I	E3	+++		++++	+
ELECTRE IS	E1	+++	+	++++	+
ELECTRE II	E3, E6	++		++	++
ELECTRE III	E1, E5, E8	+	+++	+	+
ELECTRE IV	E2	+	++++	+	+
ELECTRE TRI	E5	++	+++++	++	+++
PROMETHEE I	E1, E3, E4	+	++	+++++	+
PROMETHEE II	E1, E3, E4, E5, E6, E7, E8	+	+	+++++	++
EXPROM I	E1, E3, E4	+++	+++	+++++	+
EXPROM II	E1, E3, E4, E5, E6, E7, E8	+	++	+++++	++
MELCHIOR	E2	+++	+	+++++	+
NAIADE	E6	++		+++	+++

+: the worst method with regard to the considered criterion

+++++: the best method with regard to the considered criterion

on the criteria of non-compensation, sensitivity, practicability and workability with respect to the decision maker priorities. In terms of non-compensation, we are looking for the least compensatory method. Concerning the thresholds, we are looking for a sensitive-enough method. The practicability and workability have to be the easiest. In **Table 10**, the different outranking methods of the categories E1 to E8 are reported for each criterion, which are ranked from the worst (+) to the best (+++++).

5 Conclusion

We saw that LCA, which is a particular MCDA, needs to apply an MCA in order to model the preferences. But selecting the most suitable MCA method for a given LCA is not an easy task. Among all the possible methods, we have excluded the single-criterion and the 'interactive local judgments with trial-and-error' approaches from our study and we have limited our work to the outranking methods. Despite the fact that they remain numerous and for the same LCA, the methods give different results depending on their non-compensatory degree. Moreover, these results are more or less sensitive to thresholds and the methods are more or less practicable and workable. Depending on each and everyone's priorities in terms of non-compensatory degree, sensitivity, practicability and workability, the selected method will be different for the same LCA. A protocol has been proposed to help the LCA practitioner to choose the MCA method.

The presented form of the protocol makes it easy for the LCA practitioner to use it even if he is not a specialist of LCA. All stages of an MCDA method have been presented in the introductory section, and only the stages, which are included in the protocol, have been developed. Some parameters such as the choice of the weighting factors or the veto thresholds require the viewpoint of the decision makers and they are very subjective. For the other parameters, such as the indifference or the preference thresholds, the LCA practitioner has to respect some rules. In practice, these choices are made by a consensus among the different actors. Once these steps are fulfilled, the choice of the MCA method has to be made according to the priority standpoint regarding non-compensation, sensitivity to thresholds, practicability and workability. If several criteria seem to be important, the choice has to be made through a compromise.

The protocol, however, is not completely exhaustive because some outranking MCA methods were excluded from the protocol because they were considered either too compensatory for an environmental study or too complex to employ. The protocol represents a general approach concerning the choice of the most suitable MCA method that includes a part of subjectivity depending on the priorities of the LCA practitioner. An extension of the protocol could take into account the data quality and impact evaluation uncertainties and their influence on the choice of the MCA method. Also, it would be interesting to apply the protocol for every new outranking method development in order to see how the new methods stand with respect to the non-compensatory degree, the sensitivity to thresholds, the practicability and the workability.

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A Decision-Analytic Framework for Impact Assessment

Part I: LCA and Decision Analysis

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Abstract. Life-cycle assessments (LCAs) are conducted to satisfy the aspiration of decision makers to consider the environment in their decision making. This paper reviews decision analysis and discusses how it can be used to structure the assessment and to integrate characterization and valuation. The decision analytic concepts of objectives (goals) and attributes (indicators of the degree to which an objective is achieved) are used to describe steps of the assessment of the entire impact chain. Decision analysis distinguishes among different types of objectives and attributes; it describes how these relate to each other. Impact indicators such as the Human Toxicity Potential are constructed attributes. A means-objective network can show how the different constructed attributes relate to the objective of protecting the environment. As LCA takes disparate environmental impacts into account, it needs to assess their relative importance. Trade-off methods in decision analysis are grouped into utility theory and multicriteria decision aids; they have different advantages and disadvantages, but are all more sophisticated than simple weighting. The performance of the different trade-off methods has not yet been tested in an LCA context. In the second part of the paper, we present criteria for the development of characterization methods [Int J LCA 6 (5) 265–272 (2001)].